Cold startup behavior of natural ester based transformer dielectric liquids

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BACHELOR'S THESIS

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Abstract

The use of a dielectric insulating liquid in an environment where it would solidify, may pose a problem in transformers equipped with conservators as the solidified liquid could block the piping to the conservator, resulting in the internal pressure to increase (or decrease) to unacceptable levels in some cases when there is a change in the load. As most natural ester insulating liquids have a relatively high pour point, compared to mineral- or synthetic-based insulating liquids, they are often considered inappropriate and mineral- or synthetic-based insulating liquids are preferred due to their better low temperature properties.

As the demand for the use of natural esters grow, so does the demand for finding a solution to how transformers should be designed in order to ensure a safe operation. In this thesis, several different transformer designs have been tested and compared in order to find the best possible solution to ensure a safe operation using natural esters as insulating liquid in transformers situated in cold climates.

The final result is a working design which enables the natural ester filled transformers to be energized, even below the pour point of the ester without causing the hotspot temperature to exceed recommendations.

The tests simulate several different natural conditions with temperatures down to -25 °C. The tests were performed at ABB Transformers factory situated in Vaasa, Finland from early 2012 to late 2013.

Language: English	Key words: transformers, insulating, dielectric, natural, ester, liquid, fluid, cold, startup

EXAMENSARBETE

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Abstrakt

Användandet av dielektriska isolerande vätskor i omgivningar där de stelnar, kan utgöra ett problem i transformatorer utrustade med expansionskärl, eftersom den stelnade vätskan kan blockera rörgatan till expansionskärlet, vilket kan resultera i att det interna trycker stiger (eller sjunker) till oacceptabla nivåer i vissa fall när belastningen ändrar. Eftersom de flesta naturliga esterisolerande vätskor har en relativt hög flytpunkt, jämfört med mineral- eller syntetiskt-baserade isolerande vätskor, anses de ofta vara olämpliga och mineral- eller syntetiskt-baserade isolerande vätskor föredras tack vare deras bättre köldegenskaper.

Eftersom efterfrågan för användningen av naturliga estrar ökar, likaså ökar efterfrågan för att hitta en lösning till hur transformatorer borde vara designade för att försäkra en säker drift. I detta examensarbete har flera olika transformatordesigner blivit testade och jämförda för att hitta den bästa möjliga lösningen, för att säkerställa en säker drift av transformatorer, fyllda med naturliga estrar som isolerande vätskor, belägna i kalla klimat.

Slutresultatet är en fungerande design som möjliggör transformatorer fyllda med naturliga esters att spänningssättas, även i temperaturer under esterns flytpunkt utan att hotspot-temperaturer överstiger rekommendationerna.

Testerna simulerar flera olika naturliga väderförhållanden med temperaturer ner till -25 °C och gjordes vid ABB Transformers fabrik i Vasa, Finland, från tidigt 2012 till slutet av 2013.

Språk: Engelska Nyckelord: transformatorer, isolerande, dielektriska, naturliga, ester, vätskor, kall, start

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Tiivistelmä

Dielektristen eristysnesteiden käyttö sellaisessa ympäristössä, missä ne voivat jähmettyä, voi olla ongelma paisuntasäilöillä varustetuissa muuntajissa, koska jähmettynyt neste voi tukkia paisuntasäiliön putkia. Tämä taas voi johtaa siihen, että muuntajan sisäinen paine nousee (tai laskee) liikaa joissakin tapauksissa, joissa on kuormituksen muutoksia. Koska useimmilla luonnollisilla esteripohjaisilla eristysnesteillä on suhteellisen korkea jähmettymispiste, verrattuna mineraali- tai synteettispohjaisiin eristysnesteisiin, niitä pidetään usein epätarkoituksenmukaisina. Mineraali- tai synteettispohjaiset eristysnesteet ovat täten suositumpia johtuen niiden paremmista kylmäominaisuuksista.

Koska luonnollisten estereiden kysyntä kasvaa, kasvaa myös tarve löytää ratkaisut, kuinka muuntajien pitää olla suunniteltuja turvallista käyttöä varten. Tässä opinnäytetyössä on useita muuntajatyyppejä testattu ja verrattu, jotta löydettäisiin paras mahdollinen ratkaisu turvallisen toiminnan varmistamiseksi kylmissä olosuhteissa oleville luonnollisia estereitä käyttäville muuntajille.

Lopputuloksena on saatu toimiva ratkaisu, joka mahdollistaa tehojen kytkennän luonnollisilla estereillä täytettyyn muuntajaan, vaikka ympäristön lämpötila on alle estereiden jähmettymispisteen, ilman että muuntajan hotspot-lämpötilat ylittävät suositukset.

Testit simuloivat erilaisia luonnollisia sääolosuhteita kylmimmillään -25 °C lämpötiloissa ja ne tehtiin ABB Oy, Transformers-yksikössä Vaasassa, Suomessa vuosina 2012 ja 2013.

Kieli: Englanti Avainsanat: muuntaja, eristys, dielektrinen, luonto, esteri, neste, kylmä, käynnistys

Foreword

First I would like to thank Mr. Esa Virtanen for giving me the responsibility for the important measurements done in these tests. I am very grateful and proud to be a part of the cutting edge research in the transformer industry. Especially when this could drastically change the need for the use of fossil oils as insulating liquids in transformers. I also want to thank Esa for all excellent help and support during the tests and in the writing of this thesis.

Secondly I would like to thank Dr. George Frimpong. The tests wouldn't have been executed this well without his contribution in the form of excellent test procedures and this thesis wouldn't have been written as well without his editorial skills.

A special thank you also to Mr. Niko Pirttiniemi for handling the generators and cooler during the tests and to Mr. Mats Braskén for helping me a lot with the written part of the thesis.

Furthermore I would also like to thank Miljenko Hrkac, Alper Akdag and Max Claessens for making these tests possible in the first place.

Niklas Knuts

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Table of Contents

1 Introduction

This Bachelor's thesis was made for ABB Oy, Transformers in Vasa, Finland.

1.1 ABB

ABB in its current form was created in 1988, with the merger of the Swedish company ASEA (Allmänna Svenska Elektriska Aktiabolaget, founded 1883) and the Swiss company BBC (Brown, Boveri & Cie, founded 1891). ABB is a global leader in power and automation technologies. Based in Zurich, Switzerland, the company employs 150,000 people and operates in approximately 100 countries, [1].

1.2 ABB Finland

ABB Finland's story started in 1889 when Gottfrid Strömberg founded *Gottfrid Strömbergs elföretag* (later Ab Gottfr. Strömberg Oy) with the intention of electrifying Finland's industry. Strömberg merged with ASEA in 1987 and hence became a part of ABB in 1988.

ABB Finland currently employs around 5500, of which around 330 works at Transformers, [2].

1.3 Aim of the thesis

The aim of the thesis is to verify that the temperature and the internal pressure in a transformer do not exceed recommendations during operation in cold climates.

The use of any dielectric insulating liquid in an environment where it would solidify, may pose a problem in transformers equipped with conservators, as the solidified liquid could block the piping to the conservator, resulting in the pressure to increase (or decrease) to unacceptable levels in some cases when there is a change in the load. Also, if the liquid is in a solid state in the external radiators, it prevents the transformer from cooling itself, meaning that the temperature could rise above recommendations and hence the transformer must be tripped from the grid for safety reasons, causing an interruption.

As most natural ester insulating liquids have a relatively high pour point, compared to mineral- or synthetic-based insulating liquids, they are often considered inappropriate and mineral- or synthetic-based insulating liquids are preferred due to their better low temperature properties.

As the demand for the use of natural esters grow, so does the demand for finding a solution to how transformers should be designed to further improve the use of natural esters in cold climates.

The thesis consists in studying two different insulating liquids in two different designs, both with the aim of optimizing the design of the transformer and ensuring a safe operation using natural esters in cold climates.

2 Transformers

Invented in the late 1800s, the transformer is one of the most critical components in an electric grid, transferring energy between two circuits through electromagnetic induction. The purpose of a transformer is to minimize transfer losses as well as allowing impedance matching between mismatched circuits.

Transformers come in many different shapes and sizes, according to power, voltage class and physical location. Even though transformers today operate at close to 100% efficiency, there are some losses that generate heat (e.g. resistance in the windings, eddy currents etc.), which need to be dissipated from the transformer. Live parts also need to be insulated. The solution to these problems divides transformers into two general types: dry-insulated and liquid-insulated (Figure 1). As the names imply, the latter is insulated by liquids whereas the former is insulated by a dry solid medium and gas. The liquid and gas provide the means for dissipating heat from the windings.

Figure 1 Transformer models. Liquid insulated to the left and dry insulated to the right [3] [4]

2.1 Dry-insulated versus liquid insulated transformers

Dry-insulated transformers are almost exclusively used in high urbanized areas and the present comparison will be based on the use in an urban area.

When it comes to choosing between dry-insulated or liquid-insulated there are many factors which need to be taken into account, with the most important being the investment price and local regulations of the physical location.

Even though the price normally is the most important factor, it is considered as an economic advantage to look at the long term cost of a substation, instead of the price of the transformer(s). Liquid-insulated transformers usually demand a higher investment in the construction phase to fulfill regulations (due to fire safety), but are cheaper to operate due to lower losses and longer life expectancy (usually almost twice the lifetime thanks mainly to a lower hotspot temperature). Dry-insulated transformers are virtually maintenance free, have a significantly decreased risk of fire and enable the sub-station to be built in a much smaller physical space, [5]. The absence of liquid in dry type transformers eliminates the need for oil pits and the need to maintain the liquid.

The benefits of dry-insulation mentioned above are the key factors why dry-insulated transformers are used more frequently than liquid-insulated in highly urbanized areas, where the risk of fire and the space needed have to be kept at a minimum.

The power and voltage class are big factors when it comes to the price of a transformer. As the price of dry-insulated transformers grows rapidly with higher power, due to the need for thicker windings and higher clearances (compared to liquid insulated) to withstand the heat generated and to prevent arcs. For higher classes of transformers, it is not beneficial to use dry-insulated transformers. The level where this occurs depends on the price of the land, but is generally in the range of 500 kVA to 2.5 MVA, with dry-insulated being used up to that point and liquid insulated being used above.

This leads to the conclusion that dry-insulated transformers are often used in urban areas up to a power of 2.5 MVA, where the risk of fire is to be kept as low as possible. Liquid-insulated transformers are the norm for all classes and locations, dominating the rural areas and in urban areas where the power is over 2.5 MVA, [6].

2.1.1 Insulating liquids

As previously mentioned, insulating liquids are used in transformers with the purpose of dissipating heat from the active part(s) and to insulate live parts. The biggest benefit of using liquids over gas as insulator is the fact that they enable a smaller physical size of the transformer, a lower operating temperature, a longer life expectancy, greater overloading capabilities, higher voltage classes and better efficiency. These factors add up to the fact that liquid-insulated transformers are the most common types by far for power distribution world-wide.

The biggest drawback of liquid-insulated transformers is the liquid itself. It is at risk of catching fire in case of a serious fault, such as a short circuit or insulation breakdown. The biggest risk is if these sorts of serious faults occur and the protective equipment (e.g. over pressure and overcurrent relays, surge arresters etc.) is not working and the transformer stays energized.

There are many parameters that determine the quality and usefulness of an insulating liquid. The properties can be categorized into three categories, [7]:

1. Electrical parameters – i.e. dielectric strength (breakdown voltage), specific resistance (DC resistance) and dielectric dissipation factor (tan delta).

2. Chemical parameters – i.e. water content (moisture), acidity and sludge content.

3. Physical parameters – i.e. inter facial tension, viscosity, flash point and pour point.

Generally speaking, the electrical and chemical parameters are mainly determined by the purity of the liquid. The liquid can be purified, if needed, through a filtering and cleaning apparatus to remove impurities such as moisture and gas. The physical parameters, however, cannot be as easily improved and are mostly dependent on the specification of the liquid. This means that the physical parameters have to meet the requirements already in the specification-phase of the transformer.

Liquids get contaminated in use and age gradually. Their properties deteriorate until they are no longer usable. Gases are formed in transformers for many different reasons. For instance, gases are slowly formed as a result of overloading and rapidly formed as a result of an arc. Therefore part of the transformers' operational reliability depends on the liquid being tested regularly, not only for gasses but also to determine the general condition of the liquid. If a transformer is equipped with a Buchholz relay, there is usually a space in the relay in which the gases are collected and can be analyzed directly.

In some cases, gas analyses can be used to determine the reason for the formation of gases and to help avoid more serious faults. Gas analysis of the liquid is shortened to DGA, which stands for Dissolved Gas Analysis, which in other words means detection of how much of which gases is dissolved in the liquid, [8].

All insulating liquids contain small amounts of air (i.e. oxygen), or can be in contact with air through the conservator, which leads to oxidation. This is the most crucial factor that determines the lifetime of the liquid. The rate of oxidation depends on the temperature of the liquid (i.e. Arrhenius equation), and a rule of thumb for chemical reactions is that the reaction rate doubles when the temperature is raised by 10°C. It should be noted, however, that some oxidation reactions only occur at high temperatures, [9].

Some liquids have a natural protection against oxidation and these are known as uninhibited liquids. However, highly refined liquids do not generally possess this natural protection and require anti-oxidants as additives to minimize their oxidation process. These types of liquids are known as inhibited liquids, [10].

The buildup of gases inside transformers is the reason that the German engineer Max Buchholz is famous in the world of transformers, as it was he who invented and gave name to the Buchholz relay. The Buchholz relay is a gas relay normally situated between the transformer tank and the conservator. The Buchholz relay detects accumulation of gases as they develop inside the tank and rise upwards toward the conservator. Furthermore, the Buchholz relay also detects rapid movements of insulating liquids, which is the result of an arc when gases are rapidly formed, [11].

In order to simplify the wellbeing of customers, IEC has come up with a code for standardizing insulating liquids. Below follows a picture from IEC 61039, showing how the code is constructed, [12].

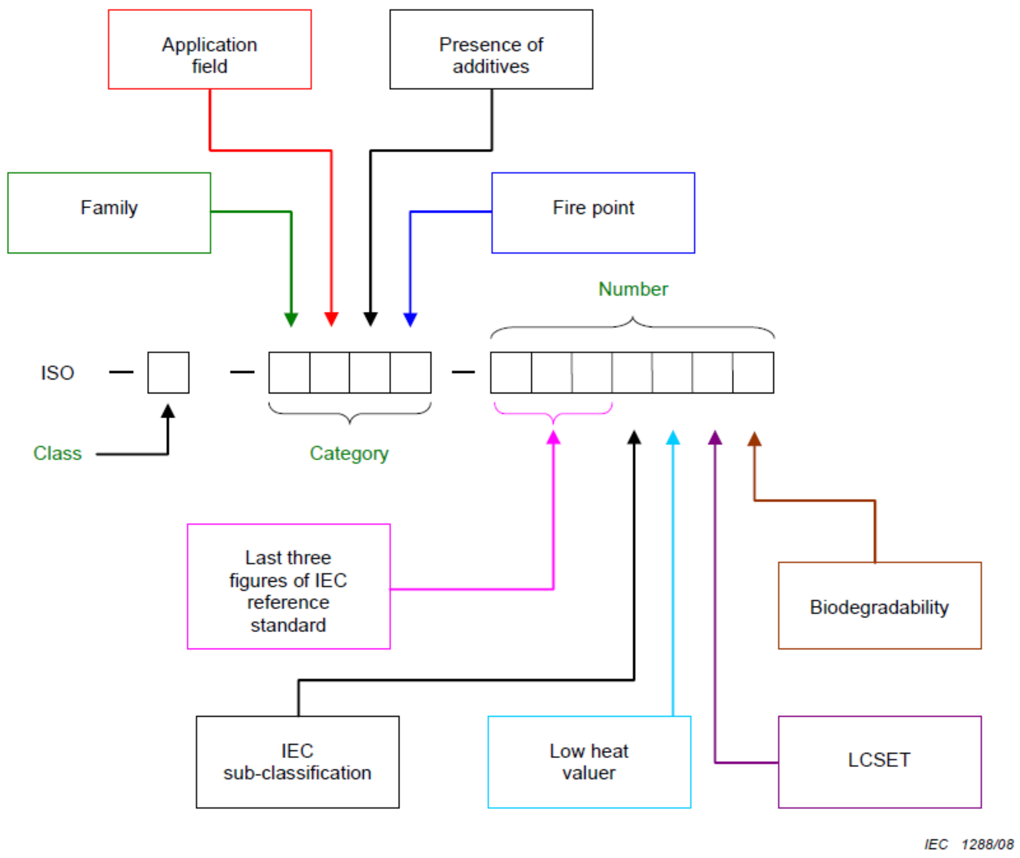

Figure 2 Figure explaining the meaning of all the digits present in the classification of insulating liquids

As can be seen in Figure 2 above, the fourth digit in the category specifies the liquid's fire class using the fire point. There are three different letters that are used in this position. These are:

– **O** if the fire point is ≤ 300 °C

– **K** if the fire point is > 300 °C

– **L** if the fire point of the liquid is not detectable.

The last letter, L, can seem fuzzy but generally means that the fire point is not detectable up to the boiling point. However, many testers also automatically abort the test due to safety reasons if a flash point is not detected 30 °C above the expected flash point or at ≥ 400 °C, [13].

Attention should be paid to the fact that there is a difference between the fire point and the flash point. The flash point is defined as *"the lowest temperature at which the vapor formed above a pool of the liquid ignites in air at a pressure of 1 atmosphere"*. The fire point is defined by "*the lowest temperature at which, on further heating beyond the flash point, the sample will support combustion for 5 seconds"*, [14].

The same source also states that the fire point is generally about +10ºC higher than the flash point. However, the difference can be much higher but the rule of thumb is that the flash point is always lower than the fire point.

The electrical insulation for internal wiring in liquid-insulated transformers rely exclusively on liquid-impregnated paper. Kraft paper (as well as pressboard materials) is based on cellulose fiber. The cellulose paper is often purified when used in electrical applications and thermally upgraded. Thermal upgrading of Kraft paper is a process where the paper is chemical treated to withstand higher temperatures. A diamond pattern epoxy resin is put on the paper so that individual layers of paper will bond to each other when cured to give a rigid transformer winding. When applied, the diamond pattern epoxy resin treatment improves the temperature resistance and thermal performance of the paper.

The type of paper used determines the highest by IEC recommended hotspot temperature in a transformer. If the thermally upgraded paper mentioned above have been used, the highest hotspot temperature in the windings can be 10 °C higher and this is the reason for why most liquid insulated transformers use a thermally upgraded diamond pattern epoxy coated Kraft paper for coil layer insulation, [15] [16].

2.1.2 Mineral-based insulating liquids

The most used type of transformer insulating liquid to date is mineral-based, which is normally obtained by fractional distillation and subsequent treatment of crude petroleum. Mineral-based liquids can be further divided into two major categories: naphthenic and paraffin. There is no easy answer to which one is more suitable, but one thing is certain; naphthenic oils have better cold-climate properties due to their lack of N-alkanes. This is also the main reason for the much lower pour point temperature and that the changes in viscosity are smaller. In other words, naphthenic-based insulating oils solidify at a much lower temperature and keep their flow ability better, [9].

This is the reason for why most of the transformers in tempered/arctic climates run on naphthenic-based oils, while it is more of an economic question in tropical conditions, i.e. the price of the liquid determines the choice of insulating liquid in tropical areas.

Even though mineral oils have a lot of good properties, the flashpoint is not one of them. As of today, most mineral oils have a flashpoint between 140…200 °C, depending on the manufacturer. The flash point is low, considering the fact that the hotspot temperature is allowed to be 150 °C according to IEC 60076-14, if thermally upgraded Kraft insulation paper is used. Also, according to the same standard, the top oil temperature (i.e. the temperature of the oil 10 cm below the cover) is allowed to be 130 °C, [15].

2.1.3 Ester-based insulating liquids

Esters are ubiquitous and chemically nothing more than a synthesized organic compound of acids and alcohols. Most naturally occurring fats and oils (e.g. the now well-known omega 3) are the fatty acid esters of glycerol, [17].

There are many different ester-based di-electric liquids on the market, but generally they can be divided into two types: synthetic esters and natural esters.

Synthetic esters are manufactured from polyol, which is a combination of an alcohol and an acid. Big benefits with synthetic esters over mineral-based oils are their biodegradability, lower pour point, in many cases a higher breakdown voltage and most importantly a much higher flash point (usually above 300 °C, which makes them a K-class insulating liquid). On the downside, they come at a much higher price, which make them competitive only in special applications, such as in the marine-, offshore- and other ATEX-businesses, [18]. ATEX comes from the French title of the European Union 94/9/EC directive, which is translated into English as "Equipment for explosive atmospheres", [19].

Natural dielectric esters have been on a steady rise since they were first invented independently in the 90s by Cooper and ABB. [20] There are many benefits with natural esters, the biggest ones being their biodegradability and the fact that they can be grown, which makes them a perfect renewable resource. Even though natural esters can be harvested from many sources (e.g. animal fats, fish oils, seeds and olive oils), the most practical ones are edible seeds, which are traded on the global market.

Even though natural esters usually have a flash point above 300 °C (K-type insulating liquid), close to 100 % biodegradability and are less expensive than synthesized esters, there are some major drawbacks such as a high pour point and a susceptibility to oxidation. The development process of natural esters has been a cat and mouse game ever since the start, trying to find the best combination to get optimal results, i.e. a low pour point and viscosity, removing the susceptibility to oxidation, while keeping all electrical properties and a high flash point, [20].

However, many of these problems have been solved, leaving only a relatively high pour point (-10°C…-20°C) compared to other insulating liquids. Even though the pour point might seem high to people living in northern Europe, one must remember that most of all transformers are positioned in such areas where the ambient temperature never drops below -10 °C and it is hence a working solution in most locations. This is where the work done in this thesis will focus. Is it possible to develop a transformer using natural esters that is safe to operate even below the pour point and if it is, how the transformer should be designed.

3 Testing

As previously stated, the aim of the thesis is to investigate how natural esters behave below their pour point and if possible, how to design the transformer to enable such an operation.

In the following tests several different temperatures and pressures were measured in order to study the operational behavior of a transformer filled with a natural ester liquid. The most critical temperatures are the hotspot and the top oil temperature. The hotspot temperatures are measured in the upper section of the windings and in between the windings, as experience from the field have shown that to be the hottest spot in a transformer. Due to fire safety and life-time expectancy it is crucial not to exceed the recommended temperatures. The top oil temperature, which is the temperature of the liquid right below the cover, is important as it gives the risk of fire in case that liquid is released from the tank. Furthermore the internal pressure is important, as there are mechanical limitations on how much the tank can withstand.

In other words, the most important measurements are there to avoid exceeding the mechanical limitations of the tank, as well as to ensure the liquid is not ignited in case of a sudden release of liquid.

The aim of the tests is to ensure a safe operation (i.e. not exceeding temperature nor pressure recommendations set by IEC) of a transformer filled with natural esters in a cold climate. In order to do so, several different tests have been performed using two different natural esters, hereafter Ester A and Ester B, with two different devices (one reactor and one transformer).

The problem with natural esters is that they solidify after long-term exposure at relatively high temperatures compared to naphthenic-based mineral oils. Problems occur if the ester is in a solid state in the piping between the tank and the conservator and there is a change in the load. Then the solidified ester is blocking the pipe to the conservator causing the pressure to increase (or decrease) to unacceptable levels in some cases. Now one plausible solution is to melt a liquefied channel to the conservator to prevent a build-up in pressure. This solution was the first thing to be tested.

At this stage, it must be mentioned that it is not only the pour point that determines the temperatures at which the ester freezes (or solidifies), [21]. In fact, natural esters in the tests done froze (or solidified) after a long term exposure to temperatures about +10 °C above their pour points. It must also be mentioned that natural esters have been proved to be safe to use, even for a cold start-up where the ester was in a solid mass in a hermetically sealed transformer.

All tests done consist of at least one cold start-up test and one low load test. The cold start-up test is to simulate the case of starting the transformer from a state where the ester is completely frozen in all parts of the transformer, whereas the low load test if to simulate the case of a falling ambient temperature and little or no load on the transformer.

Previous to the current tests a normal heat run test was performed in room temperature to obtain results for comparison. These tests differ from a normal heat run test where the resistance of the windings is measured in order to calculate the temperatures of the winding as well as the temperature rise in the windings. The reason for not measuring the resistance of the windings is that it is not considered necessary to know their average temperature, only the hotspot temperature.

The reactor that has been used in Tests 1 and 2 is ABB Oy's own reactor for R&D purposes, and it has a rated apparent power of 396 kVA (thousand volt-ampere) and a total of 11.5 kW in losses (i.e. heat generation). All pressures mentioned in this document are given in units of bar gauge (barg).

The transformer used in Test 3 is a full-scale model, which will be taken in use later in 2014.

Figure 3 The reactor used in Test 1 and 2

3.1 Test 1 – Heaters

As with all materials, the energy needed for transforming the material from a solid state to a liquid state is high, which means that it is easier to overdo it instead of doing it twice, i.e. less work to begin with too much heating instead of too little and do it twice.

A 900 mm, 3 kW immersion heater was inserted close to the main tank outlet to the pipe, to make sure that there was a liquefied channel from the active part of the transformer and out of the main tank, as shown in Figure 4 below.

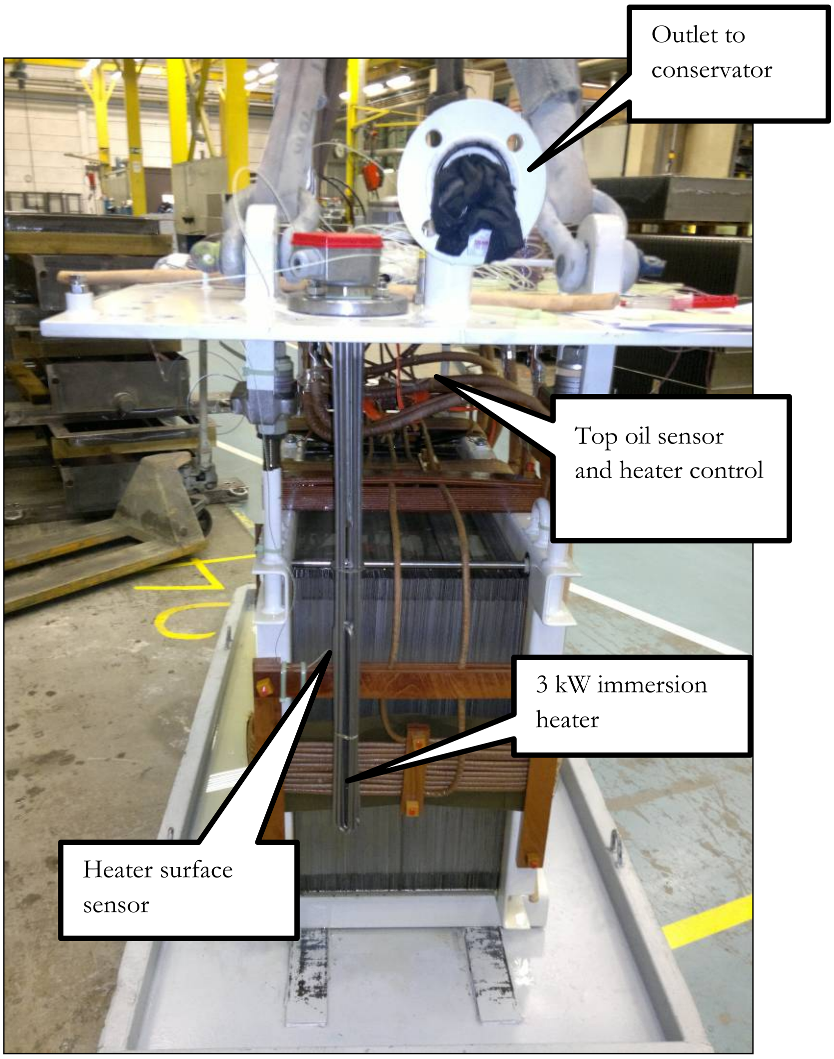

Figure 4 Heater shown in front, next to the outlet to the conservator.

The immersion heater is controlled by two separate on/off controllers. The temperature sensor to the first heater is located ~15 cm below the cover in the middle of the reactor, and the temperature sensor to the second heater is built into the top of the immersion heater. To avoid overheating, the surface temperature of the heater is also measured.

The piping to the conservator is insulated using 50 mm Rockwood and heated with several DEVi Pipeheat DPH-10 as shown in Figure 5 and Figure 6, [22].

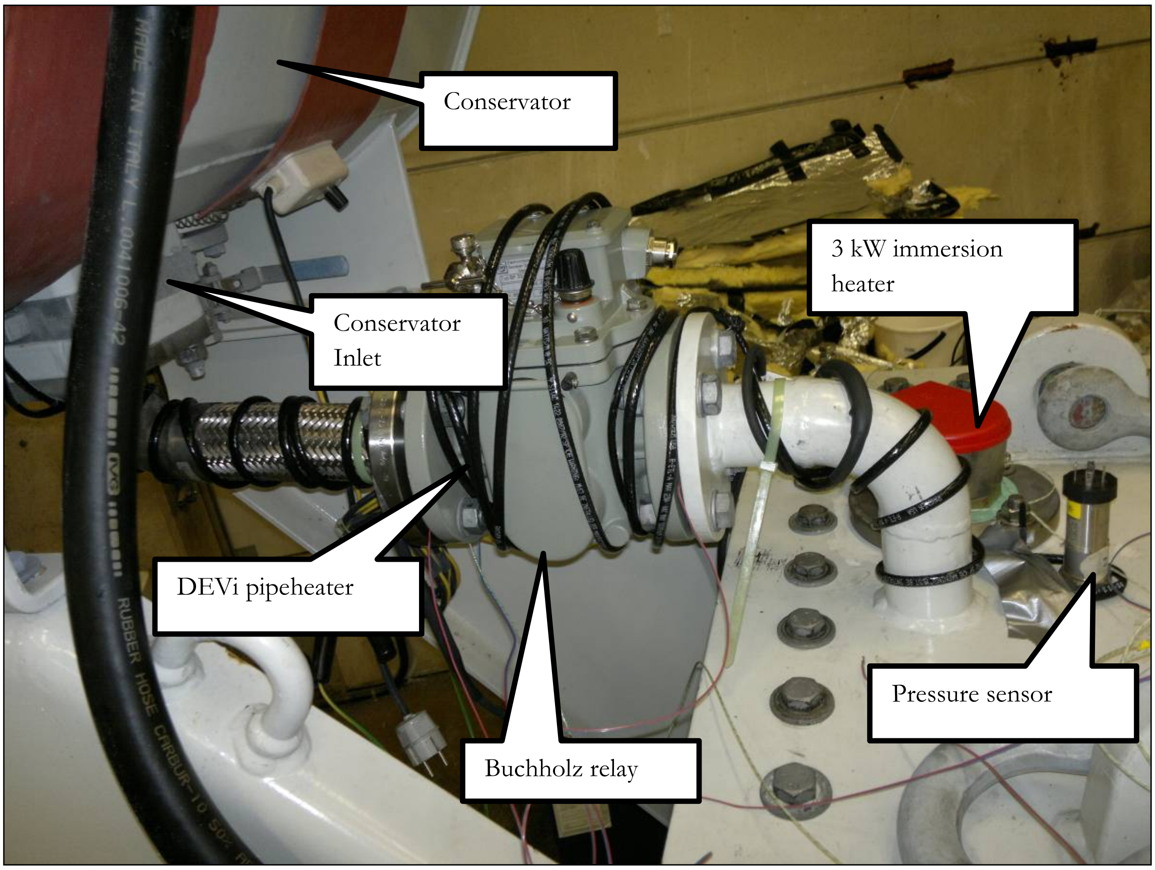

Figure 5 **Heaters used to heat the piping into the conservator**

The pipe heaters are controlled using the same on/off controller as the drum heaters wrapped around the conservator (see Figure 7). The drum heaters used are 1.5 kW each and have built-in thermostats. The sensor for the controller controlling these heaters is located at the inlet to the conservator. In addition, the pressure relief device was also heated externally with the same DEVi Pipeheater used to heat the piping to the conservator. The complete and ready to go reactor can be seen in Figure 8.

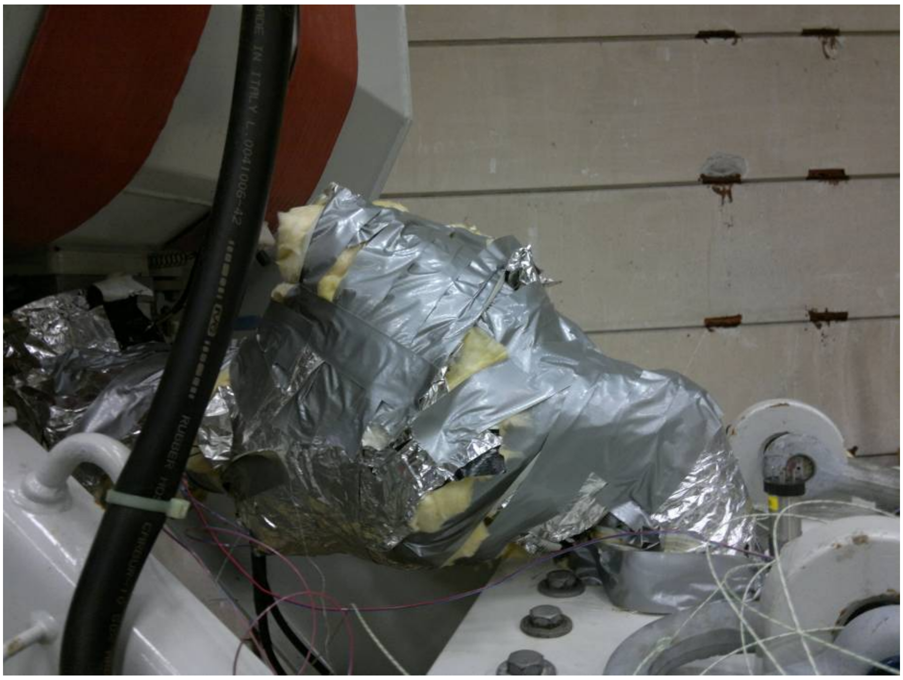

Figure 6 Conservator piping insulated with 50mm Rockwool.

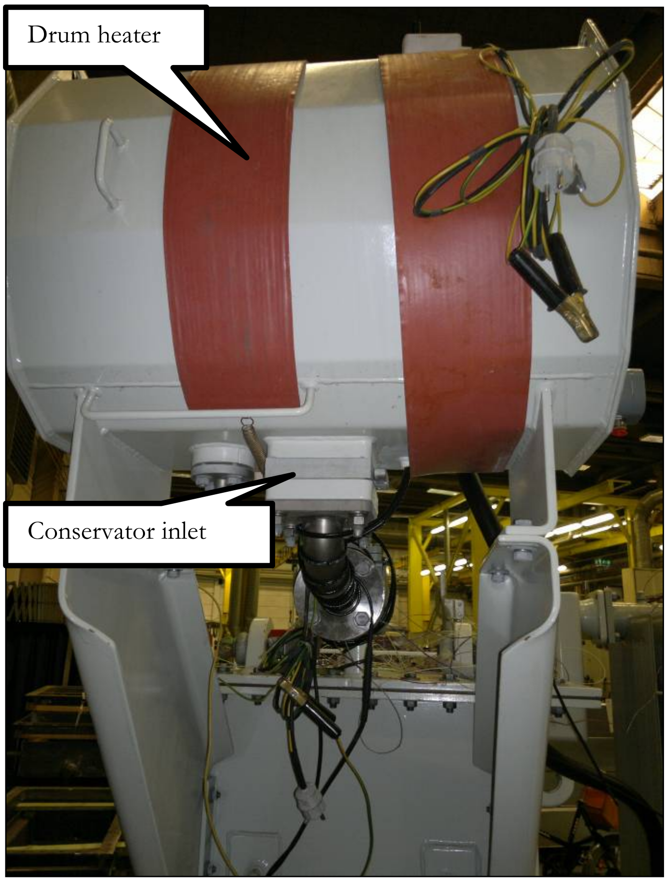

Figure 7 Drum heaters wrapped around the conservator

Figure 8 **A complete overview of the reactor used in Tests 1 and 2, wired and ready to go in the climate chamber**

3.1.1 Measurement setup

In order to measure as well as monitor all important parameters, several pressure- and temperature sensors were used. To monitor the internal pressure of the main tank, two pressure sensors were used: one close to the pressure relief device and the other one close to the outlet to the conservator. The pressure sensors used are calibrated and have a 4…20 mA output, representing -1.0…1.0 barg. To measure the temperature, several different types of temperature sensors were used. For easy placement, T-type thermo-couples were used everywhere except in the hotspots of the windings, where optical fiber sensors were used, and in the inlet/outlet to the radiators where PT-100 were used. However, the controllers to the heaters, only accepted K-types thermo-couples and these were only for the controllers themselves, hence not recorded. The temperature sensors were placed according to Table 1.

Table 1 **Placement of temperature sensors during Test 1**

Placement	Channel/Graph name
Inlet to the conservator (conservator's bottom)	Conservator inlet
Buchholz relay	Buchholz
Outlet to the conservator	Tank/Conservator
10 cm below the cover in the middle of the reactor	Top Oil
3 kW immersion heater's surface	Heater surface
Under the pressure relief device	Pressure relief
Under the active part's foot	Bottom oil
In the climate chamber (in air)	Ambient
Radiator inlet (in the piping)	Radiator top
Radiator outlet (in the piping)	Radiator bottom
Winding hotspot (between the windings)	Fiber 1…3
20 cm below the cover in the middle of the reactor	Controller to the 900mm heater
Inlet to conservator (conservator's bottom)	Controller to the conservator's heating

All temperature sensors except the ambient sensor were placed inside the reactor; none of them is on the surface of anything. The pressure sensors were screwed into holes directly in the cover of the tank according to Table 2.

Table 2 **Placement of pressure sensors during Test 1**

Placement	Channel/Graph name
Next to the outlet to conservator	Tank/Conservator
Next to the pressure relief device	Pressure relief

3.1.2 Calibration of sensors

To measure the hotspots, Neoptix's (the manufacturer of the optical fiber temperature sensors) own modules and software were used, [23]. For all other measurements, a custom made box of several Advantech's ADAM 4000-series modules [24] were used with DASYLab [25] for data acquisition. The thermocouples have been compared to a calibration device, a Beamex MC2 [26], and are in the same range as the fibers, within ±1 ºC. The PT-100 temperature sensors are estimated to be in the same range. The pressure sensors have been measured against the same calibration device as the thermocouples and then virtually calibrated (it is not possible to adjust the mA-signal from the sensor, so it has been measured and rescaled in the data acquisition software). A final error of ±0.008 bar was reached at room temperature. This accuracy isn't however necessarily the same at -25 °C.

3.1.3 The cooling/preheating to the cold startup test

Natural esters act as very good insulators when they cool down so the cooling took over a week, as shown in Figure 9.

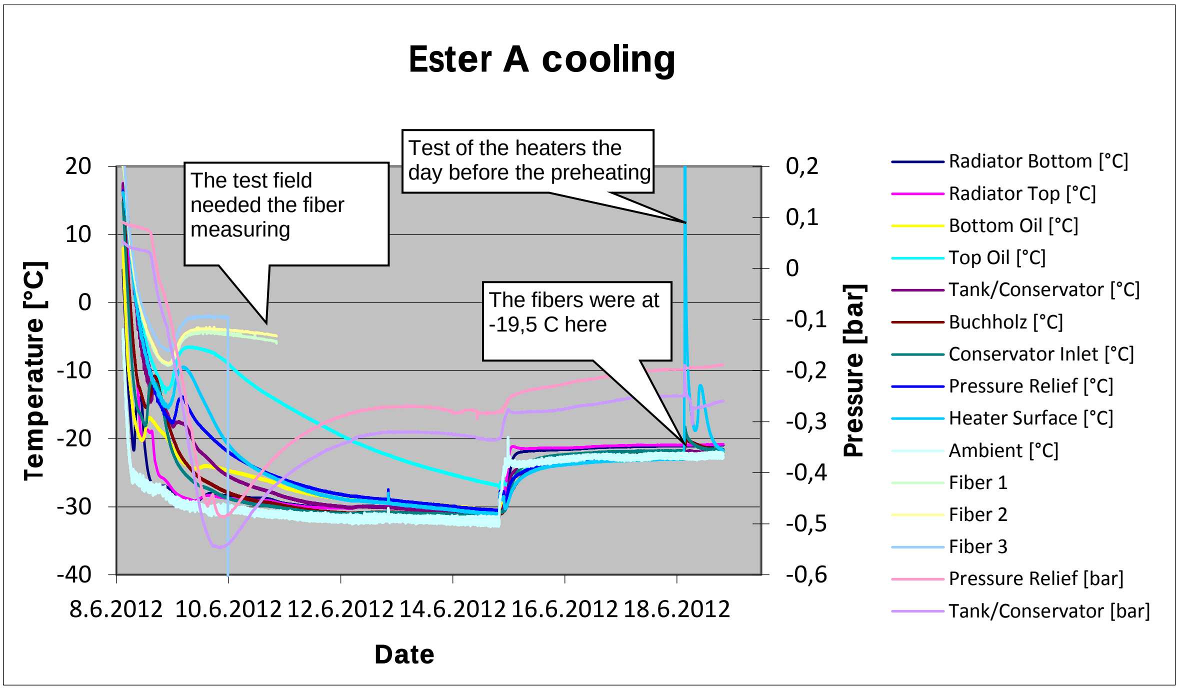

Figure 9 **The cooling graph for the reactor used in the cold startup test. Some temperature rises are seen and are obviously caused by heat released during the phase change from liquid to solid.**

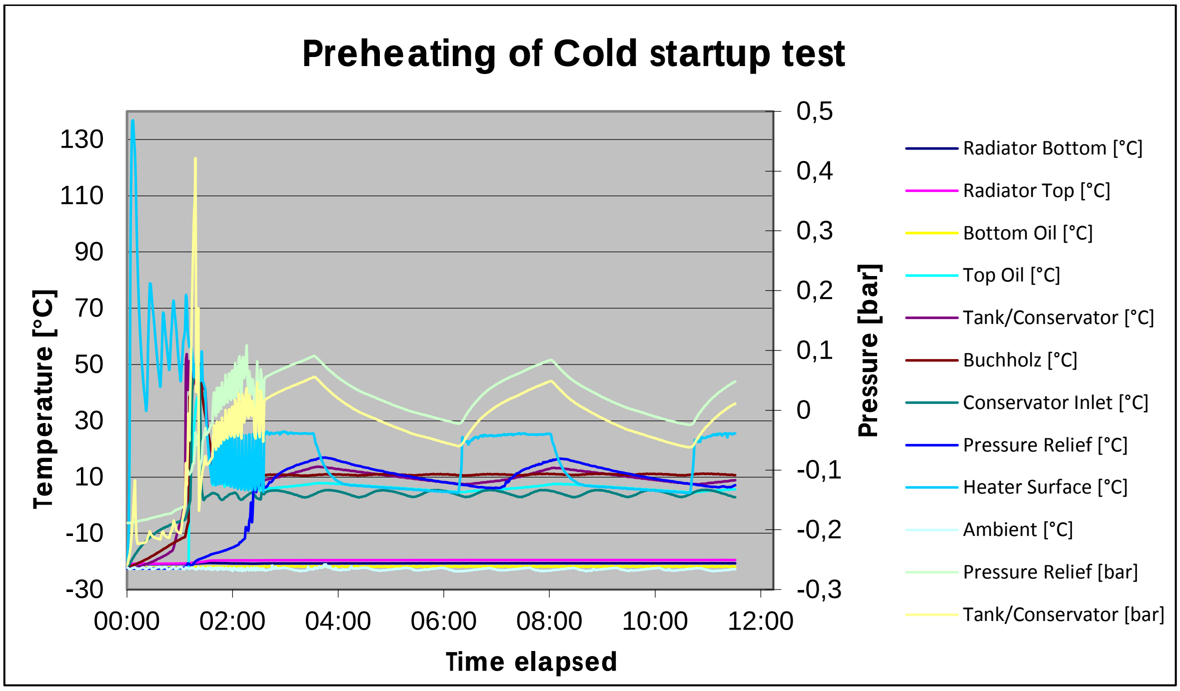

Figure 10 **Preheating graph before the cold startup test.**

Due to only one license and one module for measuring the fibers, and the fact that the test field needed it for other testing, the last days of cooling are missing from the graph. But the fibers were measured manually and got down to -20 °C in 18.06.2012 after 10 days of cooling. The light-blue peak in Figure 9 is testing of the heaters two days before the cold startup test. The test itself was run on June 20, 2012. On June 19, 2012 08:00, the core temperatures were stabilized at -20 °C and the heaters were turned on.

3.1.4 The cold startup test

The purpose of the test was to see if a cold start-up is possible with the additional heating used, thus the heating used is sufficient and correctly placed in order to avoid a pressure build-up when the ester is in a solid state and a transformer with radiators and conservator is energized with full load.

The test was performed by setting the cooler in the climate chamber to -30 °C for the first week and then to -20 °C for the remaining time needed for all the liquid to cool down to -20 °C. When cooled down to the target temperature of -20 °C in the windings, the preheating began. The purpose of the preheating is to melt a channel from the active part to the conservator, so that immediately when the transformer is loaded, the expanding and liquefied ester has a route to follow from the active part and into the conservator in order to avoid a pressure build-up. During the test the heaters were used to maintain this route liquefied when the losses from the reactor weren't sufficient to maintain it.

After preheating, the test began with energizing the reactor with full load (905 A, 250 VAC phase-to-phase, 50 Hz and a total of 11.5 kW in losses) and kept on for 9 hours. The test began at 13:00 and continued until 22:00. Besides a small pause between 14:20 and 14:50, everything went well. One can see the temperatures and the pressures in the graph in Figure 11. The temperatures of all sensors in the piping from the main tank into the conservator were above 4°C at the end of the preheating and after a rated load of 100% was applied. Since the ester is perpetually in a liquid state at temperatures greater than a couple of minus degrees, we can safely conclude that there was a path for the melting ester from the windings and the main tank to get into the conservator. However, the rate of melting in the conservator was at a much lower level than in the windings and main tank, thus the increases and dips in pressure as shown in Figure 11. During this period the maximum pressure measured was less than 0.3 bar and posed no risk of tank rupture. Nevertheless, in order to increase the rate of melting in the conservator, we let the heaters heat the conservator continuously. The pressure stabilized to just above 0 bar (there is some hydrostatic pressure from the conservator) and the temperatures stabilized more or less for the rest of the test, which proves that the test was a success. It is considered a success, as none of the important parameters (i.e. hotspot temperatures and internal pressure) exceeded recommendations and hence posed no risk of overheating nor putting mechanical stress to the tank.

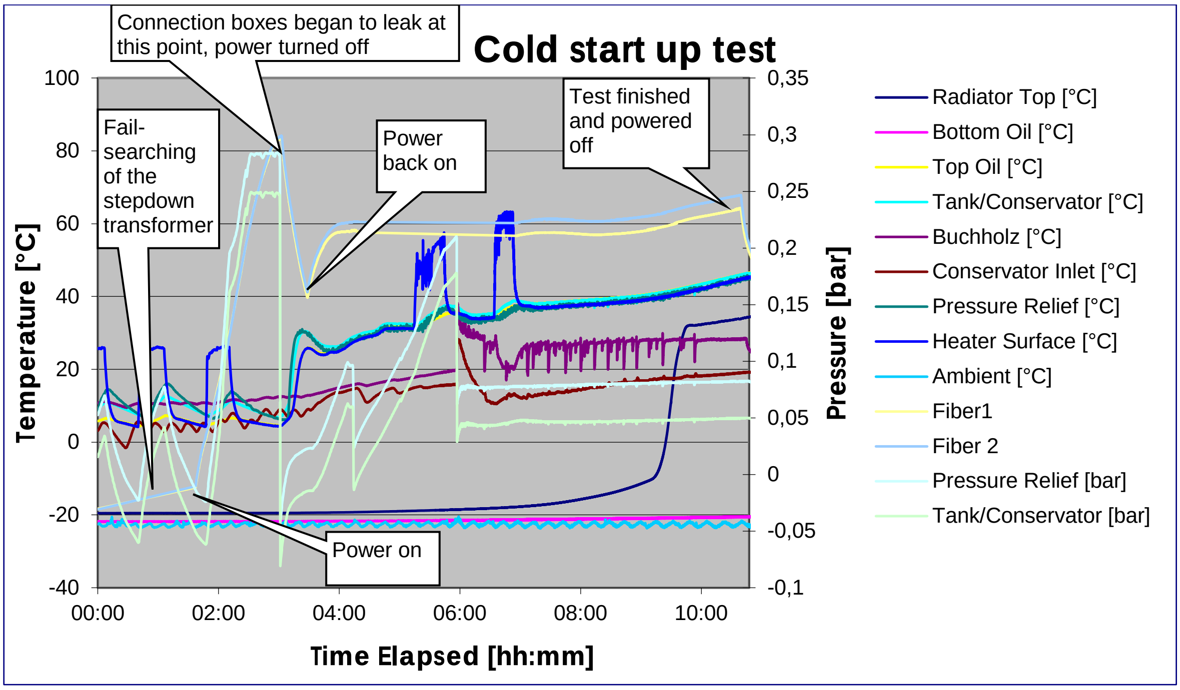

Figure 11 **The graph from the cold start up test**

Problems during the cold startup test

Optical fibers are constructed of a mixture of light carrying materials, and they depend on light for measuring the temperature. However, the solidification of the ester caused some bending and squeezing of the fiber, preventing the light from coming through the fiber, which occasionally causes a fault in the reading. During the test, 3 out of 5 connection boxes on the cover of the reactor began to leak, so we had to shut off the load and re-tighten the screws in order to continue the test. The problems did not affect the results of the test.

Improvements to the test

The biggest improvement, and one that was done before next test, was that the temperature sensor of the controller controlling the heaters of the conservator piping and the conservator, was moved from the inlet of the conservator to the surface of the ester in the conservator. To ensure that it was always on the surface of the ester in the conservator, it was attached to the liquid level gauge.

Conclusion of the cold startup test

In conclusion one can say that heating is a working solution; although it requires some minor modifications for field applications, such as logic controlling the heaters and the improvements mentioned above.

3.1.5 Low load test

The test was performed by starting from an ambient temperature of 10 °C, where all the ester was in liquid form, and simultaneously turn on the cooling and a power equivalent to 10% of the rated power of the transformer. In numbers, this means that we set the cooler to cool down the climate chamber to -22 °C and put a 50 Hz, 90.5 A and 25 VAC phase-to-phase load on. We kept the 10% load on for about 41 hours. At this point, all temperatures were stabilized and then the power was increased to 100% (50 Hz, 905 A and 250 VAC phase-to-phase, 11.5 kW in losses) in order to test a sudden increase in load when the ester is half-frozen. Full load was kept on for 11 hours. When the load was turned off, so was the cooling.

All sensors were at the same location as in the first part of Test 1, except the temperature sensor to the controller, which had been moved from the inlet of the conservator to the liquid level gauge inside the conservator.

Results of the low load test

The biggest surprise that happened was that the ester started to circulate naturally through the first panels of the radiators after 10 hours of full load. A low load was shown, in this specific reactor, not to be sufficient to maintain a liquefied channel to the conservator, even when started from a liquefied state. Without the additional heating used, the ester would have frozen quickly in the piping between the conservator and the main tank and would have blocked the flow to the conservator. The test also proves that the placement of the heating used and the thought behind it are correct for this type of tank and that no additional heating is necessary for starting the circulation in the radiators. The recorded data can be seen in Figure 12.

The temperature sensor to the controller controlling the heating of the conservator that had been moved for this test, proved to be at a better place, but may still need to be moved for optimum heating. The best solution may be if there were two temperature sensors in the conservator, one in its inlet and the other one attached to the oil level gauge. The heating should be turned on if either one of them is below +5 °C or if the piping and conservator had separate controllers and sensors.

The test results are very pleasing and considered a success with the same explanation as the first part of Test 1; the hotspot temperatures and internal pressure were well below recommendations throughout the test, thus it can be concluded that it is safe to operate the reactor in these conditions.

Conclusion of the low load test

It can be considered that only sufficient time is required for the circulation to start in external radiators, and if the expanded liquid can escape into the conservator before the circulation starts, the hotspot temperatures and internal pressure stay well below recommendations.

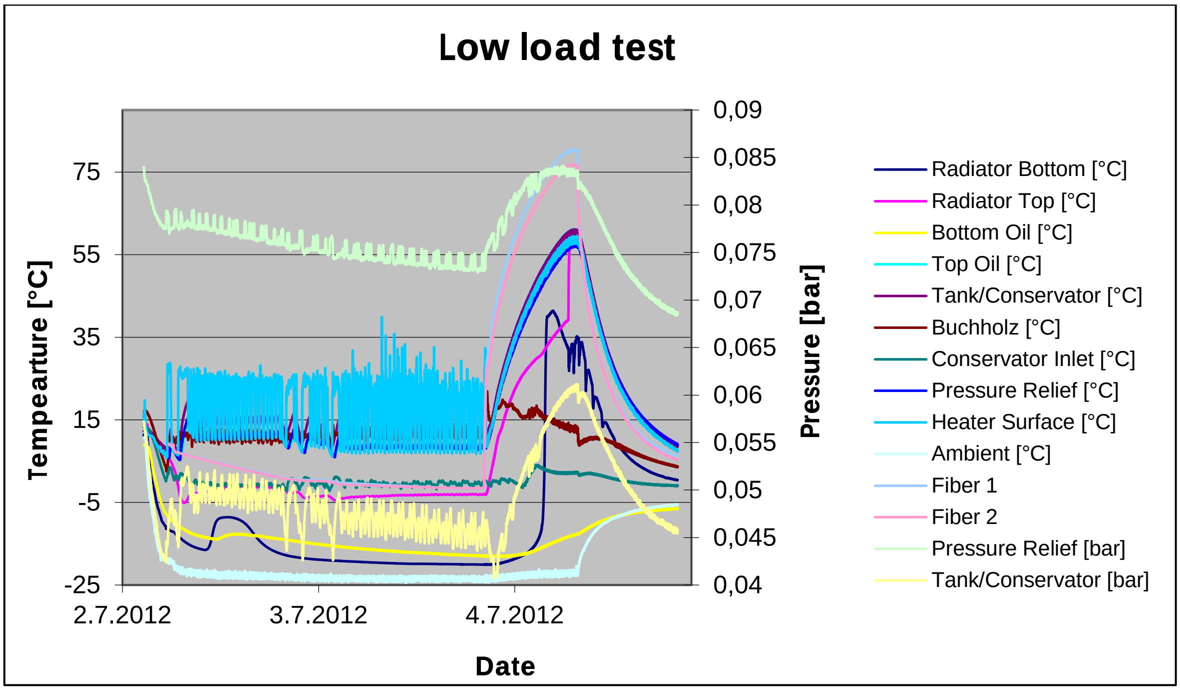

Figure 12 **The temperatures and pressures recorded in the low load test.**

3.1.6 Conclusion of Test 1

The results of Test 1 are very satisfactory. The reactor was never even close to overheating, even though no circulation occurred in the radiators in the cold start-up test. This proves that the tank itself can be sufficient for dissipating the heat generated by the losses. The pressure also stayed below acceptable limits, which proves that the ester was in a liquid state in the piping to the conservator. This in its turn proves that sufficient heating was used and was correctly placed.

3.2 Test 2 – Gas blanket

Even though the heaters in Test 1 proved to be a working solution, it is not necessarily the best one. With this in the back of our minds, it was decided that the best solution was to test it with a gas blanket design. As it was proved that the reactor used didn't overheat, everyone involved were certain it would work flawlessly with the gas blanket design, but it still had to be proven experimentally.

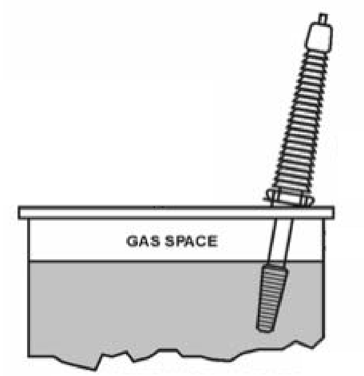

Figure 13 An overview of a typical gas blanket transformer

3.2.1 Gas blanket types

A gas blanket design means that instead of a conservator there is a gas blanket under the cover into which the liquid can expand. There are three different methods of designing a transformer with a gas blanket; free breathing, closed circuit and sealed.

The free breathing method uses two pressure valves, one high pressure valve that breathes out the gas into the air when the pressure is too high, and another low pressure valve that breathes in air if the pressure is too low. This may sound worse than it is to people outside the business but let me explain why it is not. The most common gas used is nitrogen and normal air consists of around 78% nitrogen and 21 % oxygen and 1% other gases (of which 93% is argon), [27]. Considering that the gas blanket consists of pure nitrogen before it is taken into operation, and breathes in and out a couple times a year (as variation in temperature depends only on the load percentage and the ambient temperature), the nitrogen level stays so high that a potential refill of nitrogen is only carried out as part of the annual maintenance of the transformer.

The second method for a gas blanket, which is the one mostly used today, is a closed circuit. This system is much more expensive than the free breathing, but also much better. To some extent is the system like the free breathing method, but instead of breathing in normal air it breathes in from a bottle of nitrogen attached to the transformer, which eliminates all unwanted gases (mainly oxygen as it causes oxidation).

The third system, which is used in the next test, is the sealed method. As the name implies, everything is completely sealed and allows no breathing. This is very seldom used as it adds much more mechanical stress to the tank, but on the other hand it is perfect in this case as it enables the same reactor used in Test 1 to be easily tested with a gas blanket design. On the other hand the filling of nitrogen and insulating liquid must be more accurate to avoid a too high (and too low) pressure inside the tank. Also, regarding all gas blanket methods it is important to calculate the liquid level so that it constantly stays above the inlet to the radiators to allow circulation.

3.2.2 Preparations of Test 2

As proven in the previous Test, the use of Ester A in transformers with external radiators and/or conservators in cold climates is impossible without additional modification of the tank. These modifications consist of several controlled heaters which liquefies a channel from the active part to the conservator, so that expanding ester can escape and hence prevent the internal pressure of the tank from increasing (or decreasing).

As mentioned above, the method used for the gas blanket is the sealed method. The tests that were performed were a series of tests to verify a safe operation using Ester A in cold climates.

The tests that were performed were:

- A heat run test in room temperature
- A cold startup from -25°C with 100% load
- A cold startup from -25°C with 50% load
- A cold startup from -10°C with 100% load
- A cold startup from -10°C with 50% load
- A low load test

The 100% load is equivalent to 900 A, 250 VAC phase-to-phase, and 11.5 kW in losses, while a 50% load is equivalent to 450 A, 125 VAC phase-to-phase and 2.5 kW losses. One should notice that 50% load isn't the same as 50% losses and all persons involved were aware of this. Thus it was chosen to be a more reality-based approach than 50% of the losses, as end-users of reactors are only interested in the current instead of the losses.

First the runtime was specified to '*until radiator outlet is above 0°C*', but this was later changed to at least 12 hours (except the heat run in room temperature, which was done until the hotspot stabilized). The low load test was the first cold test to be run and hence the power was cut when the outlet from the radiators was above 0°C. As the load in the 50% tests was so low, the feed could be taken from the grid and not from the generator, so there was no need for supervising the tests and hence the reactor could be kept on longer.

3.2.3 Modifications made to the tank

The reactor from Test 1 was stripped of the conservator and the Buchholz relay and a riser was added to give the additional space required for the gas blanket. The finished reactor is shown in Figure 14 below.

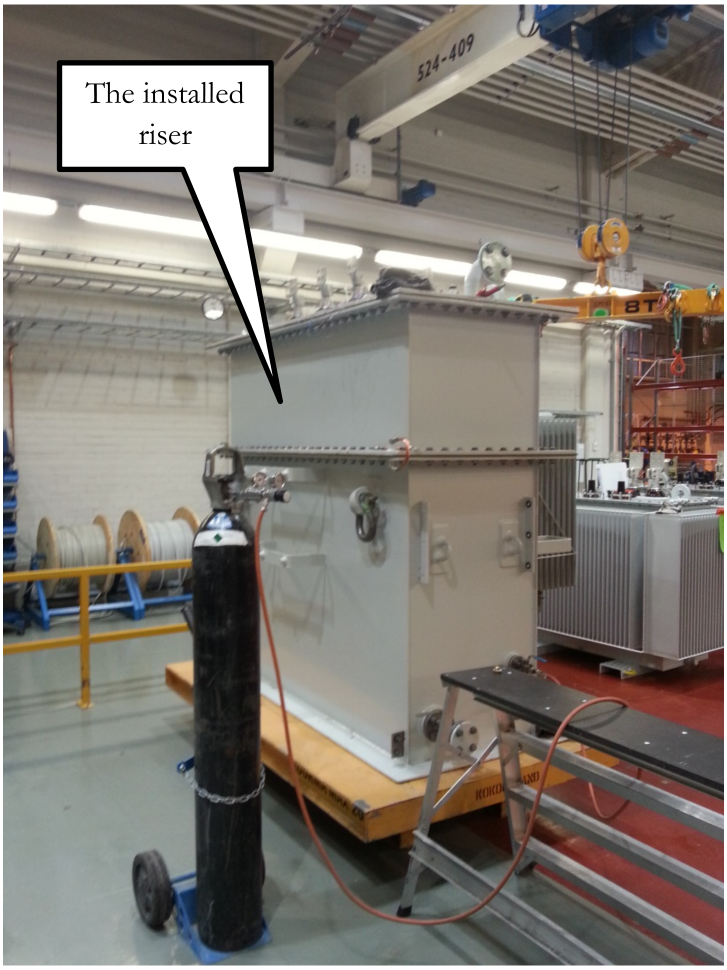

Figure 14 The reactor with the riser installed, nitrogen filling is taking place in this figure

The active part still sits on the bottom of the tank and the volume of the gas blanket is 412 liters (~15% of the total volume of the tank) in room temperature. The gas used was nitrogen, and it was filled at a slight overpressure (0.05 bar). The tank is fully sealed so there is no pressure regulation, as would most likely be the case if this had been a production unit. There is only an overpressure relief device at 70 kPa as an additional safety feature.

3.2.4 Measurements

Most of the sensors that were used in Test 1 are still in use, but some have been removed and some have been added. The sensors were calibrated before Test 1 and the calibrations are still valid in this test. To monitor the main tank's internal pressure two pressure sensors were used; one close to the pressure relief device and the other one close to the old outlet to the conservator – as in Test 1. The pressure sensors used have a 4…20 mA output representing -1.0…1.0 barg and are calibrated. Another similarity with Test 1 was that T-type thermocouples were used everywhere, except in the hotspot of the windings where optical fibers sensors were used and in the inlet/outlet to the radiators where PT-100 were used. The temperature sensors were placed according to Table 3.

Table 3 **Placement of temperature sensors in Test 2**

Placement	Channel/Graph name
3 cm below the top oil in the middle of the reactor	Top Oil
Under the pressure relief device	Pressure Relief Dev
Under the active part's foot	Bottom oil
In the climate chamber (in air)	Ambient
On top and inside of the central winding	Winding Outlet
Under and inside of the central winding	Winding Inlet
Radiator inlet (in the piping)	Radiator top
Radiator outlet (in the piping)	Radiator bottom
Winding hotspot (between the windings)	HS 1…3

All temperature sensors except the ambient sensor were placed inside the reactor; none of them is on the surface of anything. The pressure sensors were screwed into holes directly in the cover of the tank according to Table 4.

Table 4 **Placement of pressure sensors in Test 2**

Placement	Channel/Graph name
Next to the old outlet to conservator	Tank/Conservator
Next to the pressure relief device	Pressure relief

3.2.5 Tests that have been performed

A total of six tests have been done with the gas blanket designed reactor. These are:

- A heat run test in room temperature
- A cold startup from -25°C with 100% load
- A cold startup from -25°C with 50% load
- A cold startup from -10°C with 100% load
- A cold startup from -10°C with 50% load
- A low load test

They were not, however, run in that order but as shown below, as it was more convenient regarding the cooling of the climate chamber:

- Heat run test in room temperature
- Low load test
- Cold startup from -10°C with 100% load
- Cold startup from -10°C with 50% load
- Cold startup from -25°C with 50% load
- Cold startup from -25°C with 100% load

Problems before and during the tests

Some minor leaks of nitrogen occurred during the tests. These are so small that they haven't affected the results, but the starting pressure of each test is a little bit off the line, i.e. a tiny bit too high (~0.05 bar) when the test is started, as the reactor slowly breathed in air during the cool-down phase before each test. Also, the optical fibers measuring the hotspot temperatures had some reading issues, the same as in Test 1. The issues were suspected internally to be caused by frozen ester, but it turned out that there is a less sensitive option integrating the temperature over a longer time for the measuring device, and by switching to that the problem disappeared. Unfortunately this was not discovered before the last test (cold startup from -25°C with 100% load). There are tests that have been run without all hotspot temperatures, which can be seen from the absence of HS lines in the graphs from some of the tests. As a substitute the winding outlet sensor can be used as a proxy for the hotspot, as it is relatively close to the actual hotspot temperature.

3.2.6 Heat run in room temperature

To get reference points, the first test was to run a normal heat run test in room temperature. The test started in an ambient temperature of about +14°C, but the ambient temperature rose slowly as the reactor heated up the room. The power was cut after 9 hours, when the hotspot temperature was considered stabilized according to IEC. The complete graph of the results is seen in Figure 15.

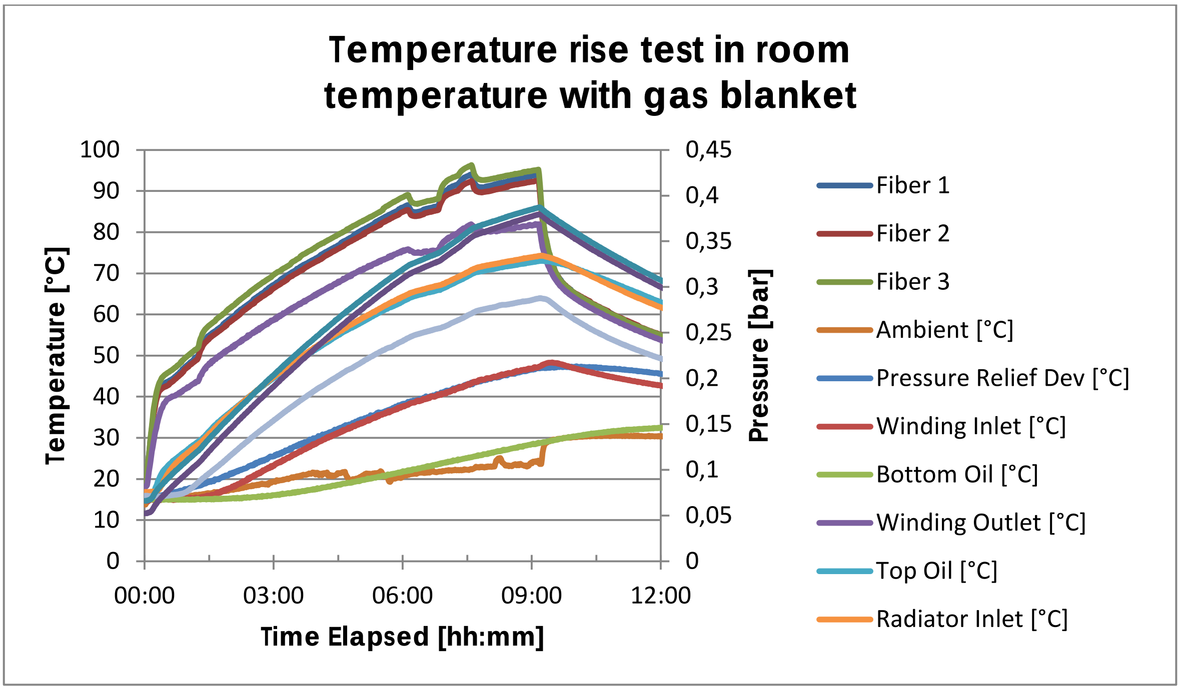

Figure 15 **Results from the heat run test in room temperature**

As can be seen in the graph above, the maximum hotspot temperature was at 95 °C and the maximum internal pressure was 0.4 bar. Both values set the foundation for further testing, as the results from the cold tests can be compared against these.

3.2.7 Cold startup from -25°C with 100% load

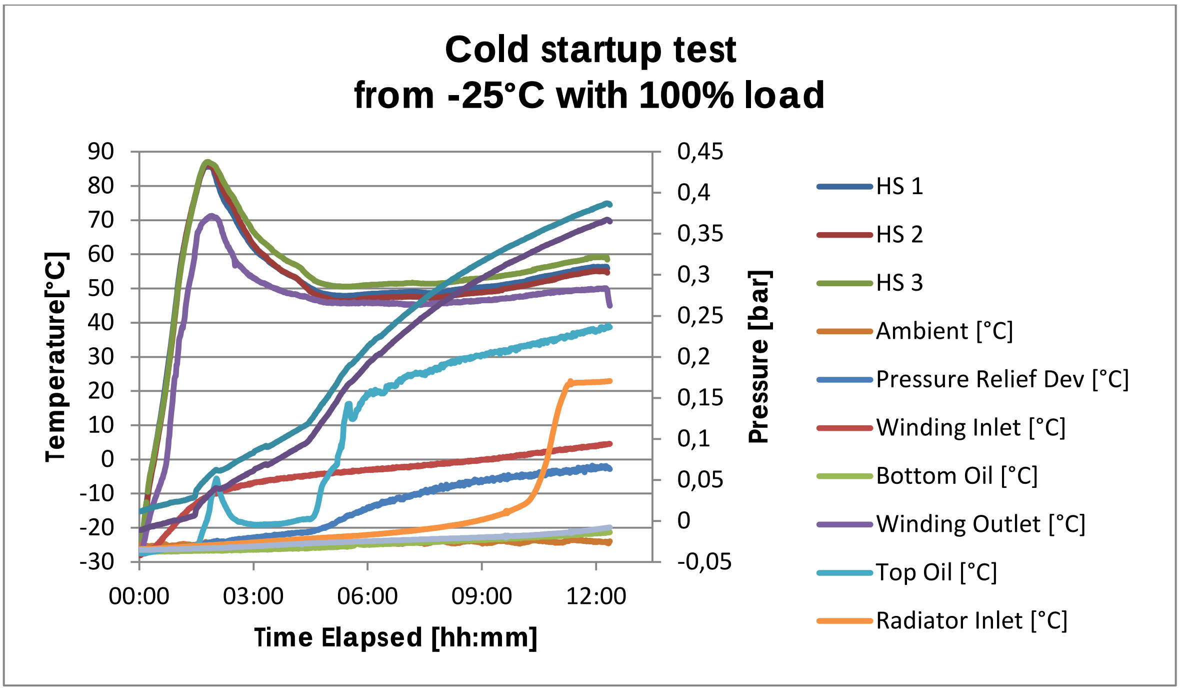

Figure 16 **Results from the cold startup with 100% load from -25°C**

If Figure 16 above is studied, one can see the typical pattern when loading a transformer filled with solidified insulating liquid; the hotspot temperatures rise rapidly until internal circulation starts around the windings, then the hotspots drop and begin to settle. At the end of the tests hotspot temperatures had begun to rise slowly again, and would most likely have continued until circulation would have begun in the radiators.

One can also see that the pressure was still rising steadily, meaning that the ester was still expanding, i.e. the average temperature of the ester still rose at the end of the test. However, it is safe to say that even if the test had continued for another 12 hours, the hotspot temperatures would still have stayed below recommendations as they were only at 58 °C at the end of the test and the recommended max value is 150 °C.

3.2.8 Cold startup from -25°C with 50% load

Notable in this test is that the internal pressure stabilized after 48 hours, which was the first time in this sequence of the tests, but it was also the longest test that had been done. When the pressure stabilized, it meant that the average temperature of the ester was no longer increasing, i.e. stabilized. In all other tests done, the internal pressure still rose slowly at the end of the test, meaning that the average temperature of the ester was still slowly rising. As mentioned before, this was one of the tests that were performed without the optical fibers measuring the hotspots. Below in Figure 17 a graph from the test is found.

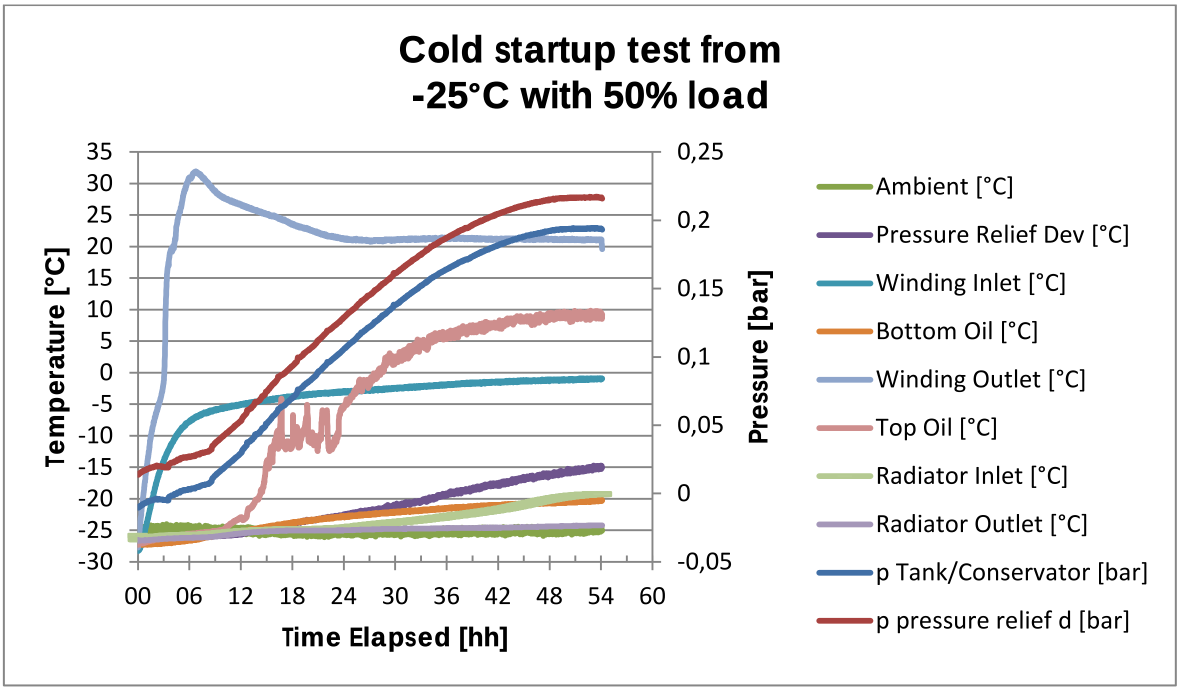

Figure 17 **Results from the cold startup test with 50% load from -25°C**

Furthermore, the surface of the ester melted after 28 hours. Internal circulation around the windings started after ~7 hours due to the fact that the temperature of the winding inlet settled then.

3.2.9 Cold startup from -10°C with 100% load

This test differs from the rest by the fact that the circulation began in the first of the radiators' panels after 12 hours of runtime. This was not the first time the circulation began, but it can be considered as the one that proves that it will begin with time. If one looks thoroughly one can see a spike in the hotspot temperatures at 7 hours, this occurred due to minor disturbances with the generator.

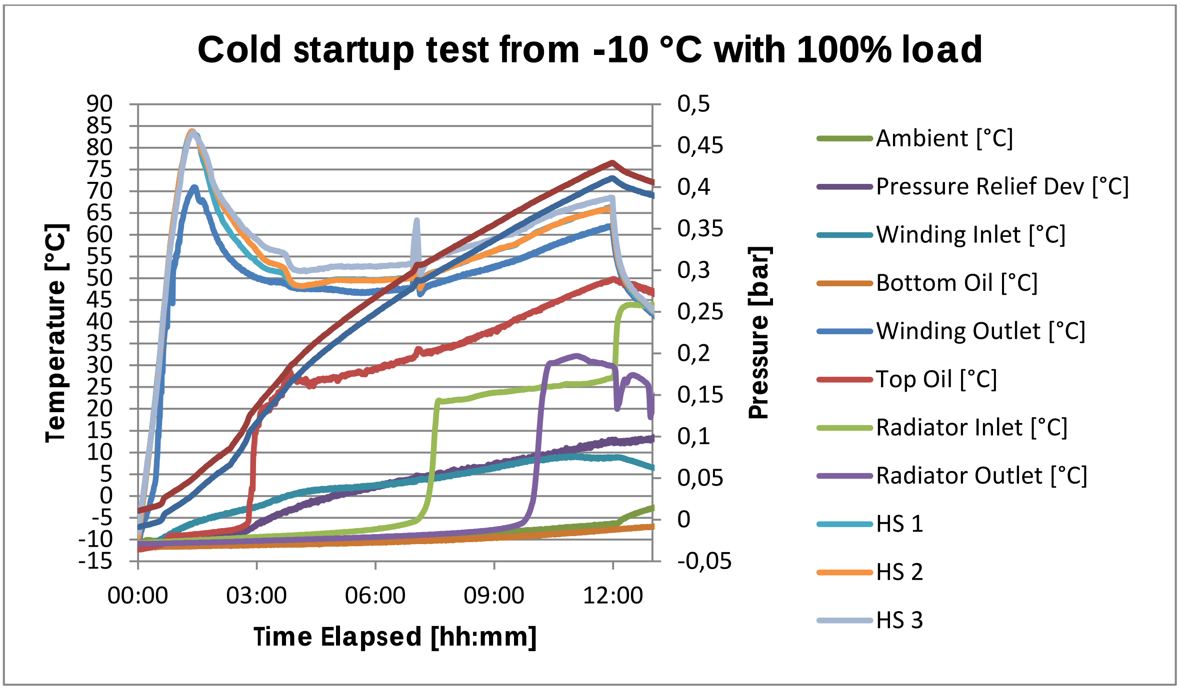

Figure 18 **Results from the cold startup from -10°C with 100% load**

At around 12 hours elapsed, the radiator outlet (out from the radiator and into the tank) became once again colder than the inlet. This is due to the fact that when the circulation began in the first panel of the radiators, it pushed a lot of cold ester through the sensor. In normal cases, the radiator inlet is always warmer than its outlet, but in these tests one hypothesis explains that as the outlet is closer to the heat source (i.e. the active part), it doesn't cool down as much on the way there as to the inlet .

The same trend in the hotspot temperatures can also be seen here.

3.2.10 Cold startup from -10°C with 50% load

The cold startup from -10°C with 50% load ran for 20 hours. As mentioned before, this is also one of the tests where one of the optical fibers didn't work.

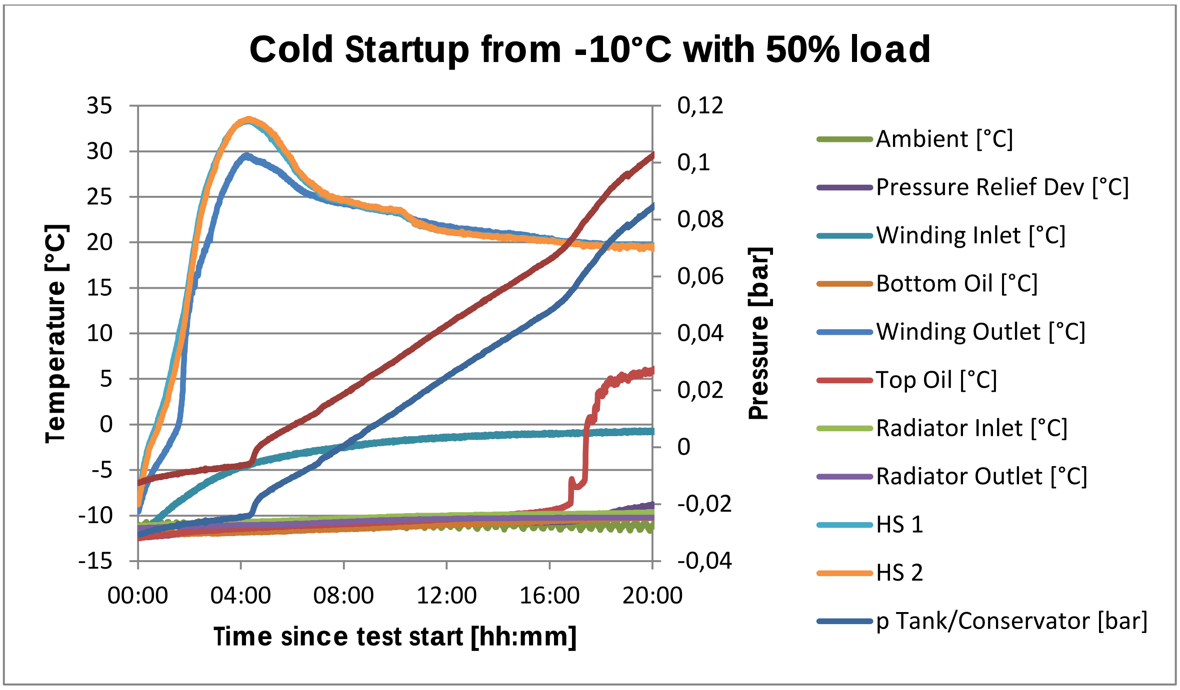

Figure 19 **Results from the cold startup from -10°C with 50% load**

In the graph above it can be seen that the hotspot temperatures show the same trend as in all other cold tests. The top oil melted after ~18 hours, which is a little more than twice as fast as in the cold startup test from -25 °C with 50% load.

3.2.11 Low load test

The low load test consists of two parts; the low load part and the full load part. Below they are split into two charts for an easier overview. There is also a short downtime (about 15 minutes) between the parts, as the connections were reconnected from grid fed to generator fed.

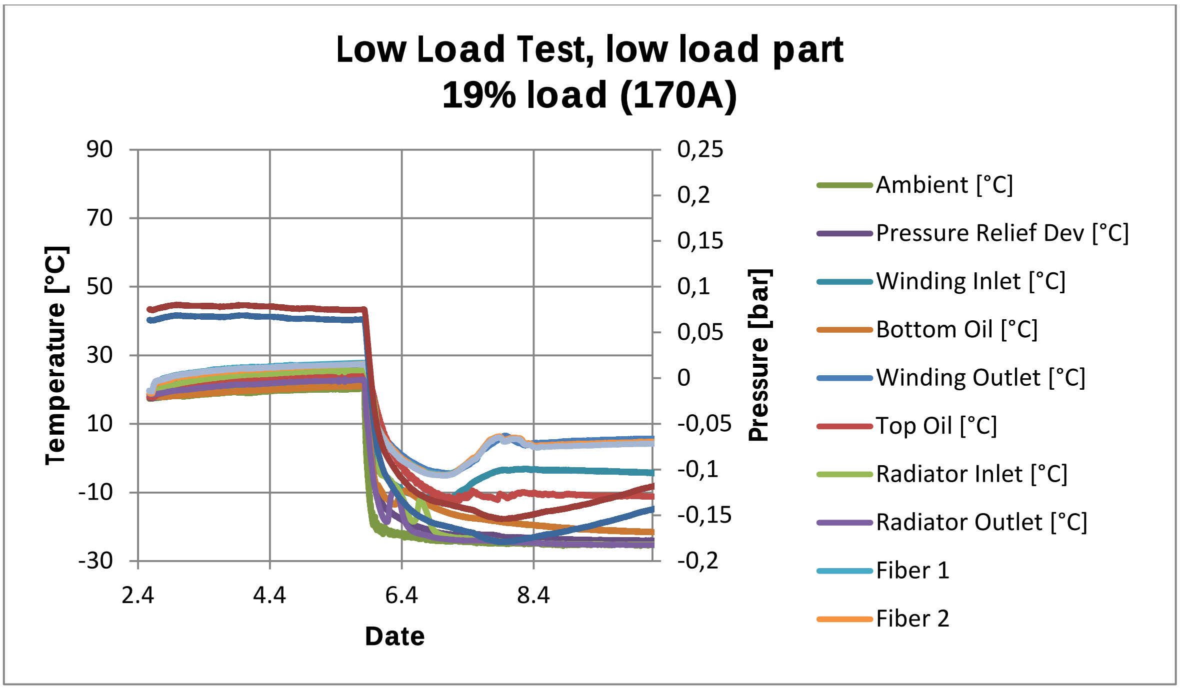

Figure 20 **Results of the low load part of the low load test**

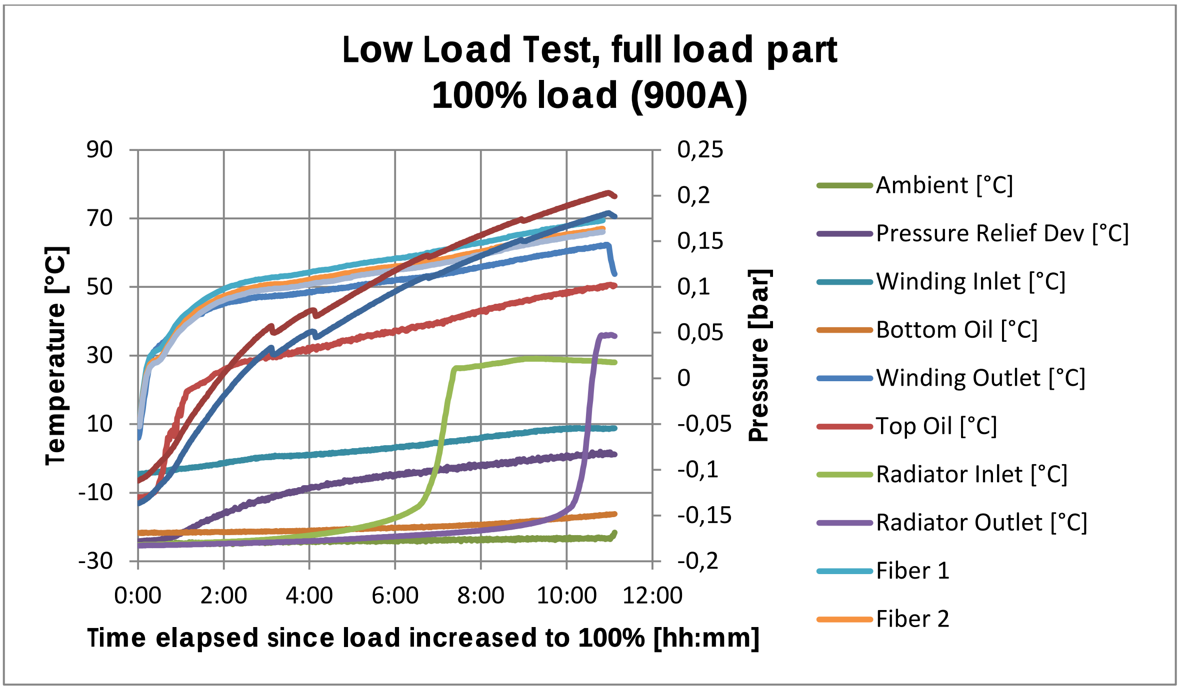

Figure 21 **Results of the full load part of the low load test**

The low load part shows once again that it is not enough to keep the ester in a liquid state in the radiators. On the other hand it is not necessary, as long as the reactor does not overheat, which it was not even close to do. In the low load part, all the ester is in a solid state, except around the windings, which allowed for some internal circulation.

3.2.12 Conclusion of Test 2

Table 5 Summary of Test 2

Test	Max HS temp [°C]	Max pressure [bar]	Top oil melted after [hh:mm]
Heat run in room temperature	95	0,39	-
Cold startup from -25°C with 100% load	86	0,39	05:12
Cold startup from -25°C with 50% load	31* *)Winding outlet temperature	0,22	28:21
Cold startup from -10°C with 100% load	83	0,43	02:51
Cold startup from -10°C with 50% load	33	0,10	17:28
Low load, low load part	6	-0,12	-
Low load, full load part	70	0,20	00:38

It can be considered proven that the gas blanket design is a working solution, which works extremely well in sub-zero temperatures without complex heating solutions. It can also be considered proven that the circulation will begin in the radiators if loaded sufficiently for a sufficient amount of time depending on the prevailing ambient temperature and the weather conditions. Neither the hotspot temperatures nor the pressure in the gas blanket exceeded the IEC recommendations, even though the circulation in the radiators didn't begin. Accordingly, the circulation itself is not considered necessary for a safe operation in cold climates.

3.3 Test 3 – Ester B

As Ester A had successfully been qualified, it was time for Ester B. Generally speaking, one can say that what set these liquids apart are additives, so Ester B has a lower pour point.

3.3.1 Tank setup

The active part sits on the bottom of the tank and the volume of the gas blanket is 1090 liters (~11% of the total volume of the tank) at room temperature. The gas used was nitrogen, and it was regulated with ABB's Inertaire System which regulates the pressure between 0.5 and 5 psi (0.035…0.35 bar). In addition there is also a pressure relief device which is set to 70 kPa (0.7 bar) as an additional safety feature.

3.3.2 Measurements

Most of the sensors that were used in Test 1 and Test 2 are still in use, but some have been removed and some have been added. The sensors were calibrated before Test 1 and the calibrations are still valid in this test. To monitor the tank's internal pressure a pressure sensor situated on a flange (filtering and filling valve) in the gas blanket was used. The pressure sensor used has a 4…20 mA output representing -1.0…1.0 barg. To measure the temperature, several different types of temperature sensors were used; in the hotspot of and around the windings optical fiber sensors were used and in the inlet/outlet to the radiators PT-100s were used and a T-type thermocouple was used for measuring the ambient temperature. The positions of the temperature sensors are given in Table 6 below.

Table 6 Placement of temperature sensors in Test 3

Placement	Channel/Graph name
In the climate chamber (in air)	Ambient
End radiator inlet (in the piping)	End inlet
End radiator outlet (in the piping)	End outlet
Middle radiator inlet (in the piping)	Middle inlet
Middle radiator outlet (in the piping)	Middle outlet
Winding hotspot (between and around the windings 1 and 2)	HS 1.1, HS 1.2, HS 1.3
Winding hotspot (between and around the windings 3)	HS 2.1, HS 2.2, HS 2.3
Winding top (on side of winding table above winding)	HS 1.5, HS 2.5
Winding bottom (on side of winding table below winding)	HS 1.4, HS 2.4

The pressure sensor was attached to a flange in the gas blanket at:

Table 7 Placement of pressure sensor in Test 3

Placement	Channel/Graph name
Filling and filtering valve in the nitrogen blanket	Pressure

Problems before and during the tests

Some minor leaks of nitrogen may have occurred during the test due to the fact that the cover was not welded nor leak tested at the time of the test. If any, they were estimated to be so small that they did not affect the results. Also, two of the optical fiber sensors (HS 1.1 and HS 2.5) in the hotspot and at the top of the windings had some reading issues in subzero temperature, even though the less sensitive option was used in the measuring device. After discussions with Neoptix, the manufacturer of the fibers, we came to the conclusion that most likely the problems had to do with the use of soft-shelled sensors, which were squeezed and bent by the freezing ester. Neoptix manufactures the same sensor with a harder shell, which should help in avoiding this type of measuring issues with liquids that are used in such temperatures that they will solidify.

The cooler was rated at 100 kW when it was new, but due to new regulations the coolant had been changed into a more environmentally friendly type, which is not as effective as the original one and hence its power is lower. This shows up in the last half of the test, when the ambient temperature began to rise slowly as the cooler's power was not sufficient to cool down the chamber. Another reason for the rising temperature was that the cooler had been continuously on for two weeks to cool down the transformer. During this time ice had built up around the fans, preventing it from cooling efficiently.

Even though the ambient temperature rose above acceptable levels at the end of the test, the test is considered as a valid one with the motivation that the ester was already circulating in the first panels at the time when the ambient temperature began to rise. Due to space limitations of the climate chamber door, only two of seven radiators could be attached to the tank and to only one side. Moreover, these radiators were ~15 cm further away from the tank as the temperature sensors (inlet/outlet) were installed in between, as can be seen in Figure 22. Figure 22 shows that there are blind flanges covering one radiator slot, which is due to the fact that the transformer stood on a customized pallet for easy movement and in order to keep the center of gravity safe, it was left out.

There was an increasing trend in the winding temperatures once all the fluid in the transformer was in a liquid state and there was circulation in several of the panels of the two radiators installed on the transformer. This increase in winding temperatures was probably due to the limited cooling capacity provided by only two out of seven required radiators.

Unfortunately the Inertaire system was not correctly adjusted before the test, with the result that the external pressure sensor settled at 0.55 bar instead of 0.35 as it should. The pressure relief unit was set to high and a bypass valve was open, which caused the pressure to be higher than it should. This does not affect the result as the main aim of the test was to investigate if the hotspot temperature exceeds the recommendations.

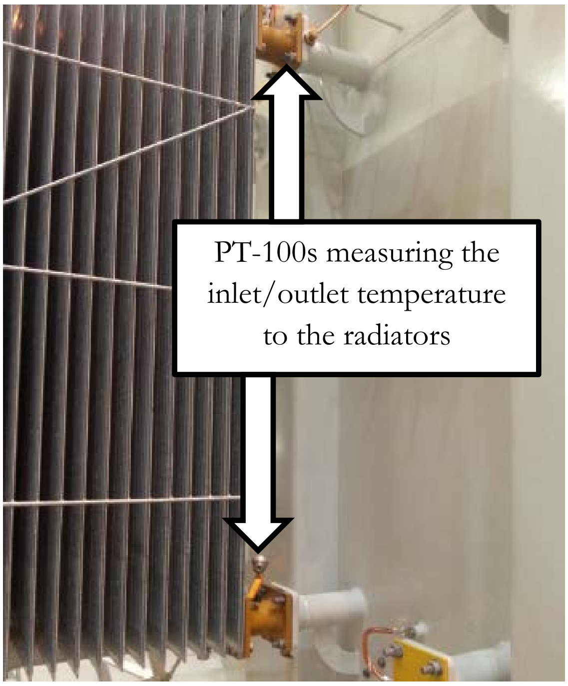

Figure 22 **Radiators with PT-100s installed**

Preparations of Test 3

The losses of the transformer were measured before the cold startup test to be a total of 83.1 kW, of which 6.4 kW is due to no-load losses and 76.7 kW is due to load losses (average value of load losses, load losses depend on the position of the tap changer). The cold start test was performed at the average of 73.3 kW, which is equivalent to ~88% of the total losses. The reason for this was that the test was performed at the rated current (942 A) instead of rated losses. The losses are smaller due to the fact that the temperature is lower and hence there is lower resistance in the windings. At the end of the test the losses were 78.5 kW, which is equivalent to 95% of the total losses.

For transformers filled with ester fluids, IEC standard 60076-14 and IEEE C57.154 specify a maximum top oil temperature for normal cyclical loading of 130 °C. The maximum hotspot temperature for normal cyclical loading is 140 °C when the solid insulation is Kraft paper and 150 °C when the solid insulation is thermally upgraded Kraft. In this test the highest hotspot was 135 °C, which can be considered relatively close to the limit, but one must remember that only two out of seven of the radiators were installed due to space limitations.

3.3.3 Cold startup test

Before the cold startup test could be performed, the transformer had to be cooled down to -25 °C. As with Ester A, the liquid insulates really well during a drop of the ambient temperature. Figure 23 shows that the total amount of time needed to cool down the transformer from room temperature to -25 °C was around nine days. The ambient temperature was dropped in steps to verify if it cooled faster if the liquid was able to circulate in the radiators during the cooldown. It was concluded that this is not the case, but instead it would have cooled a little bit faster if the cooler had been set to -30 °C from the start.

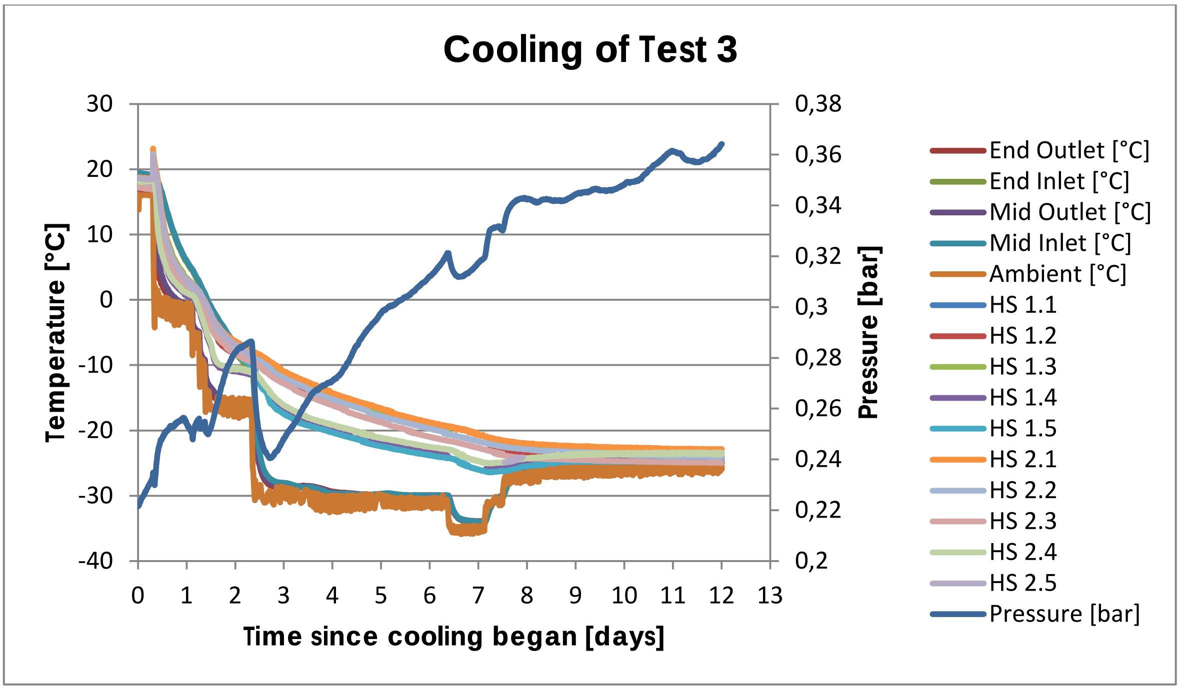

Figure 23 **Graph of the cooling stage of the cold startup test.**

The cold startup test was run until the hotspot temperatures stabilized and began to decline. Stabilization of the hotspot temperature occurred after about nine hours of runtime and the decline began shortly thereafter. The radiator inlets melted after 5 hours and their outlets followed an hour later. Circulation began in the first panels of the radiators 7½ hours after energization, or 1 hour after the outlets melted. At the end of the test there was circulation of Ester B in 13/34 panels (per radiator), and that was enough for the hotspot temperature to begin declining, which was also according to theory. The circulation can be seen in Figure 24, which is an infra-red picture taken at the end of the test. The red and green areas in Figure 24 prove that the ester is completely liquefied and hence circulating in the panels.

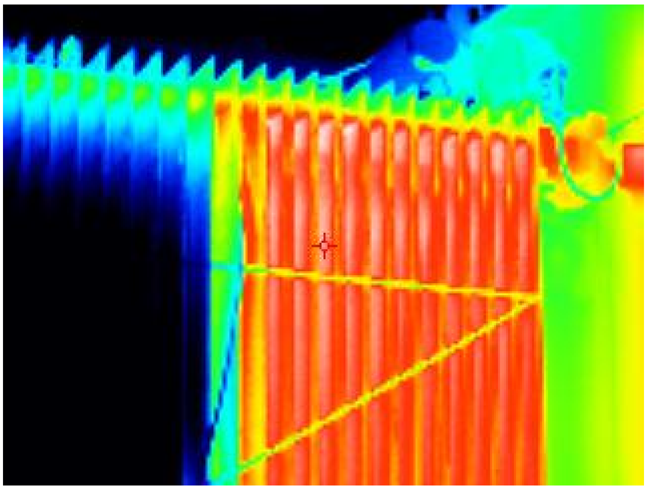

Figure 24 Circulating ester in the panels that are red and a solid mass of ester in the black ones.

Below in Figure 25 is a chart of the temperatures and the pressures acquired in the test.

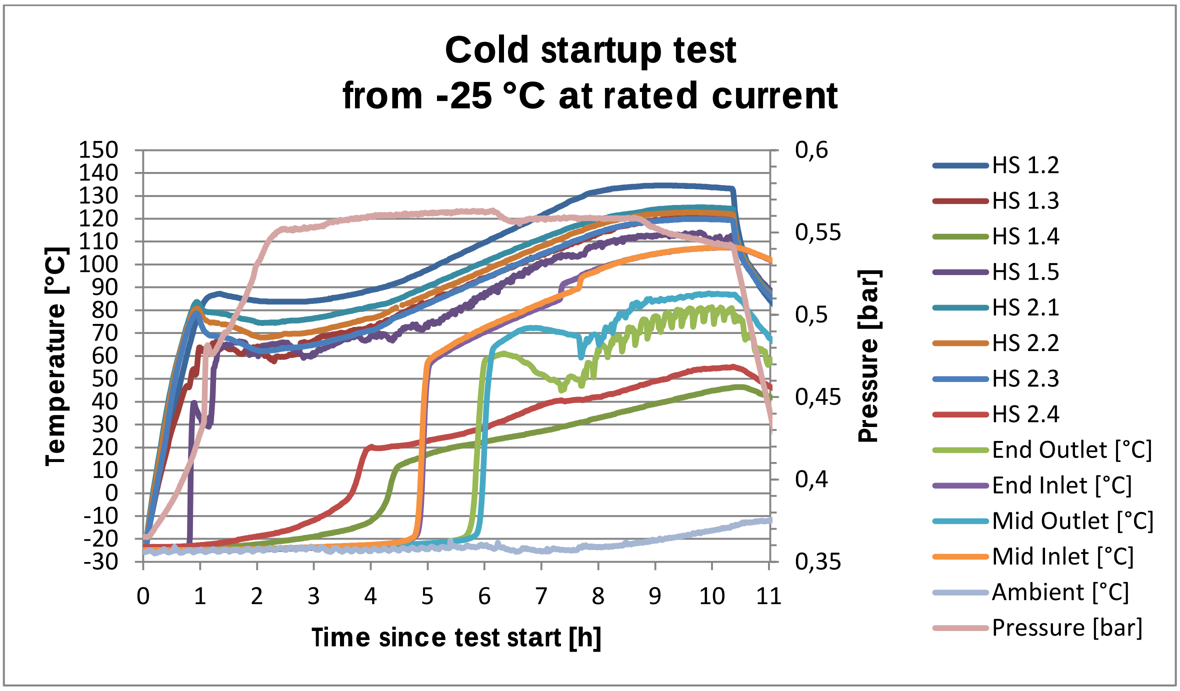

Figure 25 Results of the cold startup test.

Results of Test 3

The pressure in the tank shows a steady increase until the regulating device begins to relieve it. It can be assumed that the ester head above the windings remains completely frozen for the first couple of hours, which also occurred with Ester A in the previous tests.

If one pays close attention to the end outlet sensor from 7½ hours and forward, one can notice sudden drops in temperature. This is explained as follows: as circulation starts in a new panel, a lot of cold ester moves into the transformer, which causes the temperature to drop for a moment.

This hypothesis was verified during the test by IR-photographing and by touching by hand how many radiators were warmed up at that moment. It can be concluded that a panel in a radiator melts every 15 minutes at first and increases to around every 10 minutes at the end of this test. The IR pictures also verify that the bottom part remained somewhat below zero degrees Celcius (the bottom oil was about -5 °C according to the IR pictures taken at the end of the test) throughout the test.

3.3.4 Conclusion of the test

The results in this report show that nitrogen blanketed transformers filled with Ester B can be operated at least down to -25 °C without developing excessive pressure in the gas blanket nor excessive winding temperatures. As with Ester A, it also points out that it is critical to place the radiators as high as possible to allow the circulation to begin as soon as possible, as the bottom parts remain in a relatively cold state (less than 0 °C).

4 Results

The aim of the thesis was well achieved. The results show that one can safely energize a transformer with a 100% load, if designed as in these tests, even if the ester is in a completely solid state, whilst hotspot temperatures stay well below the IEC recommendations. The highest recorded hotspot temperature was during the heat run test in room temperature in Test 2 and it was 95 °C. Despites the fact that the hotspots was per se higher in the cold startup test with Ester B, it cannot be valid comparative as it was missing so much cooling capacity during the test. 95 °C was well below the recommended maximum temperature of 150 °C. It can be concluded that if optical fibers are used to measure hotspot temperatures, it is preferable if they have a hard shell, to avoid possible reading errors.

It is also proven that circulation in the radiators is not a necessary requirement, as the tank itself can be sufficient to dissipate the heat generated, all depending on the heat generation (losses), physical tank size and the weather conditions. It is considered proven that the natural esters used can be safely operated down to at least -25 °C, if either heaters as in Test 1 is used or a gas blanket as in Tests 2 and Test 3. Although the gas blanket design is the preferred solution as it is somewhat cheaper to implement, it doesn't require the potential expensive hours of preheating and it is a simpler solution overall.

During cold startup of a low-loss transformer, the typical pattern for the winding temperatures is a rapid increase after the application of the load. At some point the winding temperatures reach a peak and begin to decline and eventually settle. In a transformer with higher losses, the same trend shows in the beginning. However once most of the liquid has melted, the internal circulation around the windings is not enough to cool the transformer, and the hotspot temperatures rise until circulation begins in the radiators. With time, the radiator inlet and outlet may liquefy in that order.

The increasing pressure when current is applied would imply an upward movement of the block of frozen ester, as the fluid around the windings melt and expand, i.e. the frozen natural esters used in these tests maintain their lubricity even when frozen.

Furthermore, these tests are considered a big success for the future of natural esters as dielectric liquids in transformers. Based on the results, transformers filled with natural esters can be used in many more areas, opening new markets. These tests prove that with the right type of design, transformers filled with natural ester can be operated safely in cold climates, at least down to -25 °C. Still -25 °C covers most of the populated areas on our planet, so the opportunities are there.

5 Conclusions

It has been an interesting, demanding and time consuming thesis work. Alongside all other persons involved, I am very pleased with the results and I am proud to present them. This strengthens ABB's portfolio as it can offer transformers filled with natural esters to many more regions now – which is good both for the environment as well as competition. Personally I think that the use of natural ester will increase a lot over the forthcoming decades, as more and more companies want to show that they are doing their fair share to help mother earth. On the other hand, it is also an ethical question whether edible seeds should be used as insulating liquids or as food, but I will leave that question to others.

Future development that comes to mind is to test (or design) a special radiator that has thicker panels and is situated closer to the tank to allow for an earlier start of circulation. Several pipes, perhaps with different lengths or one pipe shaped as an 'E', on the end of the transformer could be enough to allow for a slow start until the 'normal' radiators kick in. This would only be to ensure that the hotspot temperatures don't exceed the recommendations before the circulation starts in the main radiators.

Finally, I would like to thank everyone involved once again, we did an amazing job!

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